MINOR STUDIES FROM THE PSYCHOLOGICAL LABORATORY OF CLARK UNIVERSITY

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XXV. THE EFFECT OF CHANGE OF INTENSITY UPON THE UPPER LIMIT OF HEARING

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It has been suggested that the dependence of the upper tonal limen upon the intensity of the stimulus resembles the relationship that holds for the retinal color zones, where an increase in intensity of stimulus results in an extension of the zone such that a color of sufficient intensity may be recognized even at the periphery.[1] Savart[2] first observed that the upper tonal limen was different for different intensities of stimulus. Zwaardemaker[3] in 1893, and Scripture and Smith[4] in 1894, noted with the Galton whistle the general dependence of the limen upon intensity.[5] The latter concluded that "the general result for all observers indicates that the pitch of the highest audible tone varies directly and almost proportionately with the intensity." The Galton whistle has been subject to errors of calibration due to a failure to control the air-pressure during use and calibration,[6] but, although the absolute values of the limens of Scripture and Smith may therefore be doubted, the increase of the limen with increased air-pressure must probably be accepted, since changes in pitch of the whistle with overblowing would produce the opposite effect.

The present study is based upon experiments with steel acoustic cylinders of the Koenig type, actuated at various intensities by falling steel balls of different weights. Since the frequencies of the cylinders were calculated only, and not calibrated, the limens lack exact absolute meaning. The value of the study lies in the relationships of the relative frequencies as indicated by the psychometric functions obtained.

The stimuli employed were seven steel cylinders, selected from an octave, g^6—g^7, divided into twenty-one parts. This division did not give exactly equal musical intervals, since it was arranged to give all the diatonic intervals with the diatonic semi-tone (112 cents) divided into two, the minor tone (182 cents) into three, and the major tone (204 cents) into four parts. The scale thus consists of musical intervals of 56, 61, and 51 cents. The frequencies of the seven cylinders used (total range 341 cents; less than two whole tones) are shown in Table II.

It should be noted that these frequencies have been calculated by the manufacturers of the stimuli (Standard Scientific Co., New York), from a calibrated bar of greater length, on the theoretical assumption that the frequency varies inversely with the square root of the length. It would be desirable to calibrate the cylinders individually, but calibration is

[1] *Cf.* E. B. Titchener, *Experimental Psychology*, 1905, II, ii, 40.

[2] F. Savart, *Ann. chim. phys.*, 44, 1830, 340.

[3] H. Zwaardemaker, *Zts. f. Ohrenheilk.*, 24, 1893, 304.

[4] E. W. Scripture and H. F. Smith, *Yale Studies*, ii, 1894, 111.

[5] In general, *cf.* Titchener, *op. cit.*, 40.

[6] *Cf.* Titchener, *op. cit.*, 32-36. Professor Ruckmick of Wellesley College will shortly publish a paper dealing with the calibration of the Galton whistle and certain related artifacts.

difficult. Koenig[7] noted that the calculated frequencies fall short of the calibration; the manufacturers of our cylinders claim to have obtained better results. For the present purpose, however, a knowledge of the exact frequencies does not matter except for the determination of the absolute position of the limen. The psychometric functions which represent relationships of sensory response to the stimulus-continuum are essentially the same so long as the stimuli represent a continuum and do not involve artificial inversions. There is no reason to believe that a series of cylinders, varying from one another only in length, give anything but a series of frequencies increasing regularly with a decrease of length. And indeed, in an experience with these cylinders in the Clark Laboratory which extends considerably beyond the limits of this experiment,[8] the fact that no inversions in qualitative psychometric functions have ever been obtained, excepting only for *B* in this experiment, indicated further indirectly that the cylinders constitute a continuous series of frequencies.[9]

The cylinders were suspended in a semicircular trough of 15 in. inside radius, of 20 in. outside radius, and 3 in. deep. The sides of the trough were padded with felt, the bottom with cotton covered by felt. The cylinders hung in a radial position, suspended by loops of dental floss each from a pair of metal strips that projected over the two edges of the trough. There was a space of 1 in. between the projecting ends of every pair of supporting strips, which left room for actuating the cylinders by a falling ball. Adjacent cylinders were 10.6° apart, *i. e.* about 4.5 in. on the average between the axes or about 3.75 in. on the average between the sides of the cylinders.

Vibration was secured by dropping a steel ball-bearing upon the cylinder from an electromagnet attached to a rotating radial arm. The magnet was centered over the center-line of the trough: thus the arm could be swung so as to allow the ball, when released from the magnet, to strike any desired cylinder. A small piece of rubber tubing at the end of the core of the magnet just kept the ball from actual contact with the steel of the core. Attached to the magnet was a small pointer, which indicated the position of the magnet on a scale fixed on each metal strip, thus controlling the exact point of impact of the ball with the cylinder.

The ball was required to strike a glancing blow upon the cylinder for the reason that it was likely to bounce and strike twice when the line of fall was the vertical diameter of the cylinder. The point of impact selected was the point of emergence of a diameter of the cylinder that makes an angle of about 4°52′ with the vertical diameter. Different intensities of stimulus were obtained by using balls of different weight as indicated in Table I. These balls were, of course, also of different size, and thus gave different heights of fall from the magnet, which remained at a fixed height. The necessary corrections were small, however, in comparison with the difference of weight, and it makes little difference whether these results are computed in terms of the weight or in terms of the energy (weight with variable height of fall taken into account).

In order to render stimuli of different sizes comparable, the arm had to be adjusted so that the point of impact, *i. e.*, the point of tangency be-

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[7]R. Koenig, *Wied. Ann.*, 69, 1899, 723.

[8]C. C. Pratt, this JOURNAL, 31, 1920, 403-406; and in another unpublished experiment by the present writer.

[9]It is a question whether the stimuli in the method of constant stimuli need to be equally spaced, or indeed whether such a statement of stimulus-distances has any psychological meaning. The matter is wrapped up with the problem of mental units and of the logic of mental measurement in general and can not be gone into here. This paper gives some indication, however, of the manner in which relative results may have scientific meaning without regard to their absolute values.

tween the spherical surface of the ball and the surface of the cylinder, should remain the same. The lateral displacement of the line of fall for a ball of radius r_1 with respect to the line of fall for a ball of radius r_2 is given by the formula:

relative displacement $= \sin a\ (r_1 - r_2)$,

where $a = 4°52'$, the angle of the diameter of impact with the vertical diameter of the cylinder. The displacements of the last column of Table I are determined in this manner.

TABLE I.

Dimensions of the stimulus. Radius, weight, height of fall, and resultant energy of the 6 steel balls, dropped by electromagnetic release on the acoustic cylinders for different intensities of stimulus. The last column gives the lateral displacement of the line of fall from the perpendicular diameter of the cylinder necessary in order to secure impact at the same point on the cylinder (*i. e.* 4° 52′ from the vertical diameter).

Ball No.	Radius (cm.)	Weight (gm.)	Height of Fall (cm.)	Energy (g.cm.)	Displacement from Center of Cylinder (cm.)
1	.225	.435	7.999	3.479	.67
2	.300	1.040	7.849	8.163	.68
3	.375	2.025	7.699	15.590	.69
4	.475	3.505	7.500	26.287	.70
5	.550	5.546	7.350	40.763	.71
6	.625	8.315	7.201	59.876	.72

The relationship for the heights of fall, h_1 and h_2, of two balls of radii r_1 and r_2 is:

$h_1 = h_2 - (r_1 - r_2)(1 + \cos a)$.

The heights of fall in Table I are figured in this manner.

The total energy of the ball at the moment of impact is the product of the height of fall by the weight of the ball, but the energy effective for actuating the cylinder is that component normal to the surface of the cylinder at the point of impact. Since, however, the one is proportional to the other, it is enough to give the total energy, which is shown in the figures of Table I.

The observers were: Dr. C. C. Pratt (*P*), Mr. M. K. Macdonald (*M*), and Mr. F. L. Bixby (*B*), all highly practised in these judgments, since they had just completed observations on a similar problem, in which the same apparatus had been used.

The *O* was seated with his back to the apparatus and 4 ft. away. The instructions were read to him: "When the stimulus is presented, you are to say 'Yes', if you hear a tone, and 'No', if you hear no tone. Try to report immediately. Be sure of your judgment. If you are doubtful, ask to have the stimulus repeated. It is no matter how often you ask; never make a judgment when in doubt."

A few trials served to indicate a critical stimulus, which was then made the central stimulus in a series of five that included two cylinders on each side of the critical one. They were presented in haphazard order, with a 5-min. rest-period after each series of 100 judgments. A short preliminary warming-up practice preceded each series. One hundred judgments were taken on each cylinder for each intensity.

Table II shows the relative frequencies for the various calculated vibration rates and for the various intensities as indicated by the total energy of the falling ball. The rows of the table give the qualitative psychometric functions, which are plotted in Figg. 1-3, and the columns give intensive psychometric functions, which are plotted in Figg. 4-6.

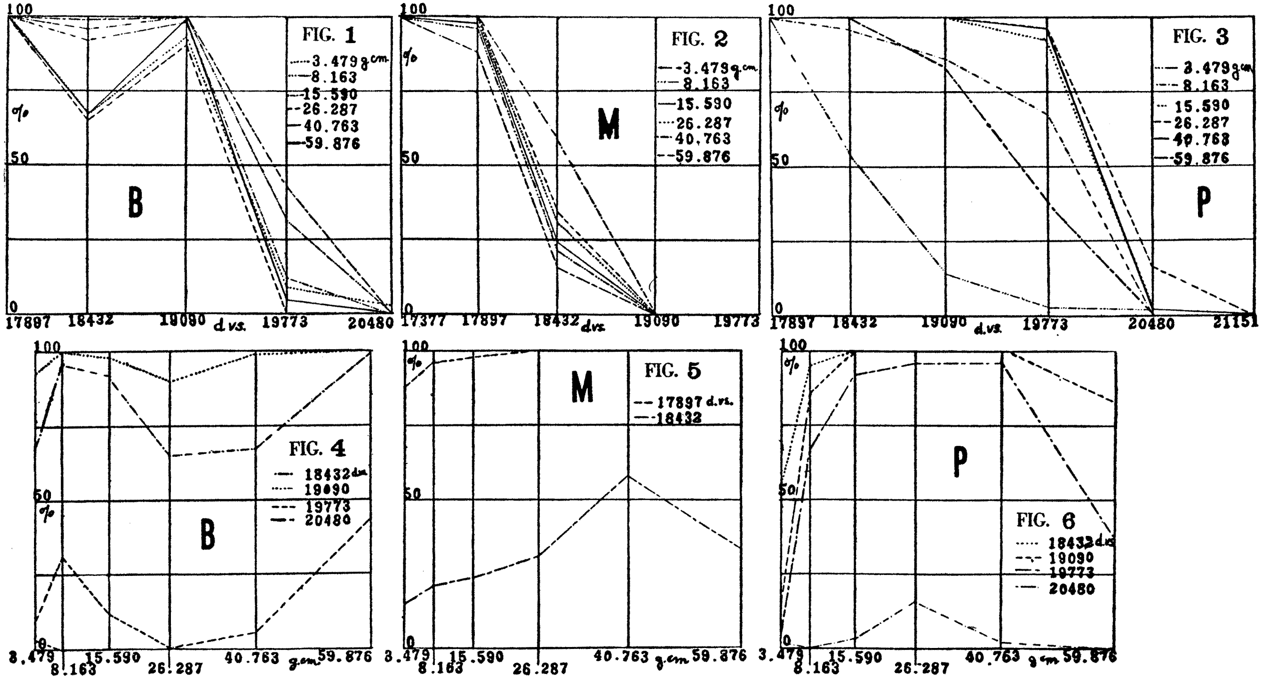
Table II

Observed relative frequencies of tones for various pitches (calculated vibration rates of the acoustic cylinders) and various intensities (energy of falling ball). The rows of the table give qualitative psychometric functions for the different intensities; the columns give intensive psychometric functions for different pitches. The 6 musical intervalls between the 7 stimuli in the table are successively from left to right: 51, 51, 61, 61, 61, and 56 cents.

Observer	Energy of Stimulus (g.cm.)	Calculated Vibration Rates of Stimuli (d.vs.)						
		17377	17897	18432	19090	19773	20480	21151
	3.479		100	67	93	9	3	
	8.163		100	96	100	31	0	
B	15.590		100	92	98	12	0	
	26.287		100	65	90	0	0	
	40.763		100	67	99	5	0	
	59.876		100	99	100	43	0	
	3.479	100	88	15	0	0		
	8.163	100	96	21	0	0		
M	15.590	100	98	24	0	0		
	26.287	100	100	31	0	0		
	40.763	100	100	58	0	0		
	59.876	100	100	34	0	0		
	3.479		100	55	14	3	2	
	8.163		100	96	86	67	0	
P	15.590		100	100	100	92	3	
	26.287			100	100	96	16	0
	40.763			100	100	96	2	0
	59.876		100	100	83	38	0	

In plotting the psychometric functions and in computing limens from them, we have used simply linear interpolation between the successive points. It is immediately evident from an inspection of the form of these psychometric functions that the *phi-gamma* hypothesis has no general validity for all psychometric functions: it is certainly not applicable here. We might have used Lagrange's formula as an indifferent hypothesis: a smooth curve that passes through all the observed points. A smooth function is probably more natural than a broken line, but, as Urban has shown, Lagrange's formula may lead to impossible interpolations, since it may give values above 100% and below 0%, and thus probably is equally in error in other regions. There is no particular justification for the straight line, except the practical one that it is easy to determine and renders interpolation easy. The work with Lagrange's formula is exceedingly laborious and there is no reason to believe that it gives any 'truer' result. It is good common sense, when we are equally ignorant of all hypotheses, to accept the least irksome.

By linear interpolation, then, we computed the terminal qualitative limens as a function of intensity. The results are shown in Table III and are charted in Fig. 7.



FIGG. I-3. Qualitative (pitch) psychometric functions of tones for various intensities (energy of falling ball, g. cm.). FIGG. 4-6. Intensive psychometric functions of tones for various pitches (d. vs.). Observers *B*, *M*, and *P*. Graphic representation of the data of Table II.

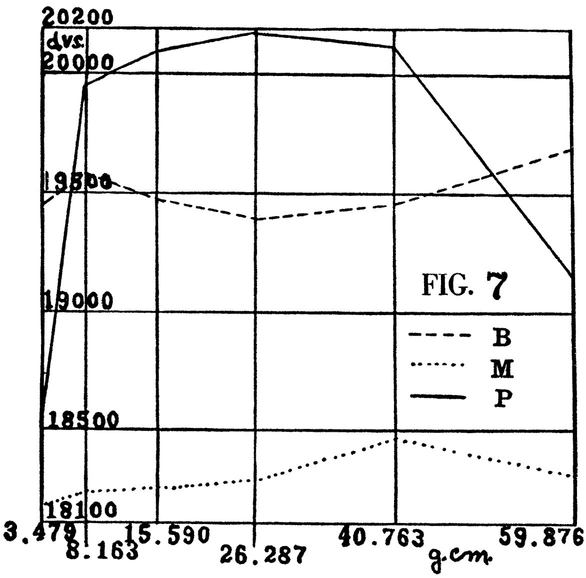


FIG. 7. Qualitative limens for various intensities of stimulus. Observers: *B*, *M*, and *P*. Data from Table III.

TABLE III

Qualitative limens, calculated from the rows of Table II by linear interpolation between the relative frequencies that include 50%.

Energy of Stimulus (g.cm.)	Observer		
	B	*M*	*P*
3.479	19,439.63	18,175.49	18,512.24
8.163	19,587.82	18,238.46	19,952.38
15.590	19,471.20	18,244.02	20,106.24
26.287	19,393.55	18,284.63	20,179.52
40.763	19,446.03	18,454.73	20,118.97
59.876	19,639.12	18,302.30	19,140.86

There are decided individual differences of qualitative terminal limen (Fig. 7). Except for the two extreme values of *P*, the individual differences are so much greater than the intensive variation for a single *O*, that the curves do not overlap.

The function that the qualitative limen is of intensity is different for different individuals. With increasing energy of stimulus, there is for *M* a decided rise followed by a decrease; for *B*, an increase, followed by a decrease, followed by a marked increase; for *P*, a great increase, followed by a great decrease (see Fig. 7). The form of the function is similar for *M* and *P*, but different in degree. *B*'s function is different from *M*'s and *P*'s, but similar in degree of variability to *M*'s. In no case are we able to say that the qualitative limen "varies directly and almost proportionately with the intensity."

A casual inspection of Fig. 7 might seem to indicate that the variation of the qualitative limen with intensity was insignificant and a matter of chance, perhaps of uncontrolled conditions. Inspection of Figg. 1-3 shows, however, that the relationships indicated by the form of curves in Figg. 7 hold consistently throughout the course of the psychometric functions. Fig. 7 is plotted for the limen defined as that value of stimulus most likely to give 50% positive judgments of tone. If, instead, the values of stimulus most likely to give other percentages are taken (*e. g.*, 75%, 25%), we find the same relationships holding. This fact is shown graphically in Figg. 1-3 by the fact that the various psychometric functions cross but rarely, that they have in general the same form, and that they lie in general in the same order throughout their courses. The argument for significant individual differences in these liminal functions is thus as follows: the differences cannot be an artifact of the cylinders, for the same relationship for a given *O* occurs with every stimulus capable of exhibiting difference; the difference cannot be an artifact of the different balls, for the same set of balls is involved for every cylinder for every *O*, and the different *O*s give different results; therefore the *O*s remain the only possible variant. It follows further that, if the differences in the course of the limen are significant, then the fact that the limen within these qualitative and intensive limits does not consistently increase with increase of intensity is also significantly established.

In general it is apparent that with material of this sort the mere statement of the limen gives but little of the available information. The interpreter of the data needs to keep the entire psychometric functions in mind if he is to have a complete knowledge of sensory response to stimulation at the upper limits of hearing. Especially does this fact appear in the case of *B*, Fig. 1. It will be seen that the relative frequencies for 18432 d. vs. are lower than for the stimuli on each side. One suspects at once a defect in calculation for the 18432 cylinder, but such an explanation will not hold. Neither *M* nor *P* shows an inversion at this point, nor did any inversions occur in extensive series taken in another experiment with these cylinders and with three other *O*s besides the *O*s of this experiment. Presumably therefore the group of psychometric functions may be taken as indicating for *B* a hypaesthetic region at 18432 d. vs. or else a hyperaesthetic region at 19090 d. vs. If the inversion in any of the psychometric functions had been great enough to cause the curve to cross the 50% abscissa, then it would have been possible to demonstrate statistically a tonal lacuna at 18432 d. vs. and a tonal island at 19090 d. vs., or, in psychophysical terms, a TR followed by an RL followed by a second TR. In a case of this sort it is apparent that no mere calculation of limens would ever give the total picture of auditory sensitivity. Even if we were willing to select some other frequency than 50% for the definition of the limen, we should not help ourselves, for there is no single abscissa that cuts more than three of the six psychometric functions, although all six functions demonstrate the same facts.

Figg. 4-6 show the intensive psychometric functions plotted from the columns of Table II. They represent the same facts taken from another aspect. Had the qualitative upper limen increased continuously with intensity, we should have been able to state the same fact by saying that the intensive lower limen (threshold) increased with pitch. In fact the psychometric functions of Table II are really not curves at all, but surfaces of relative frequencies plotted against pitch and intensity.

It is not possible in most cases to compute the intensive limens for the reason that a wide enough range of stimuli was not used. Two functions for *P* and one for *M* do cross the 50% abscissa. *P* would appear in this region to show a tendency toward an "intensive island." The function for 19773 d. vs. shows a lower limen at about 7 g. cm. and an upper limen

at about 56 g. cm. Between these two intensities, tone is heard more often than not. The other functions for *P* show the same general course, although they do not admit of the computation of limens.

There are individual differences among *O*s in the course of the intensive psychometric functions. *P* shows an increase followed by a decrease, both of an amount that is large in comparison with the qualitative change. *M* shows an increase followed by a decrease of amounts small with respect to the qualitative change. *B* shows consistently an increase, followed by a decrease, followed by an increase, all of a lesser degree than the amount of the qualitative change. It would thus appear that *B* has a region of intensive hypaesthesia followed by a region of intensive hyperaesthesia, that is to say, there are certain intensities which of themselves tend to increase the relative frequency with which tone is heard and which are more effective than are higher and lower intensities. The significance of these psychometric functions is indicated, as it was for quality, by the consistency among the functions for each *O*.

The degree of precision of the sensory response at these ranges of the tonal scale is indicated by the interquartile range of the qualitative psychometric functions, *i. e.* the change of pitch which would change the relative frequencies of the report of tone from 25% to 75%. In the eighteen qualitative psychometric functions, the interquartile range varies from 250 d. vs. to 830 d. vs., with an average of 494 d. vs. This average corresponds to a musical interval of about 40 cents, which is less than a quarter-tone, and shows a sensitiveness of discriminatory response not ordinarily expected in the region of the upper limit of hearing.

Conclusions

1. A complete account of sensitivity in the upper regions of hearing can not be given by the computation of limens; the complete psychometric functions must be considered.

2. Both qualitative and intensive psychometric functions can be determined simultaneously; the former indicates the qualitative upper limits of hearing, the latter the intensive lower limits for these qualities.

3. For any given *O* the qualitative psychometric functions for the different intensities are similar, and the intensive psychometric functions for the different pitches are similar.

4. There are individual differences in the forms of both the qualitative and the intensive psychometric functions. Both kinds of functions may show significant inversions or reversals and are not even approximately ogival in form.

5. Qualitative sensitivity, as indicated by the limen and also by the entire psychometric functions, does not, within the limits of this experiment and for these three *O*s, increase consistently with an increase in the energy of the stimulus, but follows a less simple law which varies for the individual *O*.

6. The qualitative psychometric functions indicate for one *O* the existence of a qualitative region that is hypaesthetic with respect to the next higher pitches. This phenomenon is presumably similar to the phenomenon of a tonal lacuna, but less extreme. Similar variations occur in the intensive psychometric functions.

7. The interquartile range of the qualitative psychometric functions is on the average about a quarter-tone, indicating an unexpected sensitiveness of discriminatory response.